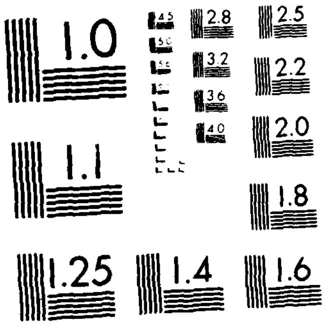
AD-A195 313 REPORT ON AN OVERSEAS VISIT TO USA RELATING TO THE THERMOELASTIC MEASUREM..(U) AERONAUTICAL RESEARCH LABS MELBOURNE (AUSTRALIA) A K WONG FEB 88 ARL/STRUC-TM-481 1/1

UNCLASSIFIED DODA-AR-004-590 F/G 20/11 NL

END
DATE
FILMED
8 88



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

(4)

ARL-STRUC-TM-481

AR-004-590

AUSTRALIA

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Structures Technical Memorandum 481

REPORT ON AN OVERSEAS VISIT TO USA RELATING TO THE THERMOELASTIC MEASUREMENT OF STRESSES 16-21 AUGUST 1987 (U)

by

A.K. WONG

Approved for Public Release

FEBRUARY 1988

AR-004-590

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
AERONAUTICAL RESEARCH LABORATORY

Structures Technical Memorandum 481

REPORT ON AN OVERSEAS VISIT TO USA RELATING TO THE THERMOELASTIC MEASUREMENT OF STRESSES 16-21 AUGUST 1987 (U)

by

A.K. WONG

SUMMARY

This report describes a short overseas visit made by the author to the United States in 1987. The purpose of the visit was to attend the 31st Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, and to present an invited paper.

DSTO FISHERMEN'S BEND

POSTAL ADDRESS: Director, Aeronautical Research Laboratory,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

CONTENTS

1. INTRODUCTION

The author visited USA during the period 16-21 August 1987 to attend the 31st Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering. The symposium, hosted by SPIE (Society of Photo-Optical Instrumentation Engineers), was held in the Town and Country Hotel, San Diego, California, and comprised some 20 technical conferences, 61 tutorial short courses, and a comprehensive instrument exhibit.

The primary purpose of the author's visit was to present a paper entitled "Recent Work on the Stress Dependence of the Thermoelastic Parameter" at the symposium. The paper deals with one aspect of the thermoelastic effect which was recently discovered by ARL, and has important implications to stress analysis techniques which utilise the thermoelastic effect. The most important conclusion from ARL's work is that this effect may be applied to the measurement of residual stresses. As a result, tremendous interest has been generated, and Sira Ltd., which is the manufacturer of an existing thermoelastic dynamic stress analysis device SPATE (Stress Pattern Analysis by measurement of Thermal Emission) was prepared to partly fund the author's visit.

2. THE EXHIBITS

The instrument exhibit was comprehensive, with several hundreds of displays and demonstrations of optical and optoelectronic equipments. There was a clear emphasis on lasers, infrared detection and imagery, and data processing softwares and systems.

3. THE CONFERENCES

The technical conferences were held over the period 17 to 21 August. Due to the large number of topics involved, up to seven or eight concurrent sessions were run for most of the five days. Judging by the enormous variety in the subjects for discussion, optics and optoelectronics appear to have an important role in most fields of science and engineering such as astronomy; medical research; non-destructive testing of materials and military applications to name just a few. The sessions attended by the author were mainly associated with non-destructive testing, fatigue and fracture, and strain/stress measurements. Of particular interest were the talks on the use of thermography in the detection of damages, voids and moisture contents in composite materials. The subjects covered in the fatigue and fracture sessions include moire, speckle and holographic interferometries, method of caustics, as well as photoelastic techniques.

During the strain/stress measurements session, four papers relating to the use of SPATE were presented. They were:

(1) "Review of SPATE applications at the National Engineering Laboratory", by W.M. Cummings and N. Harwood. The talk was presented by Mr. Cummings of NEL who highlighted many successful applications of SPATE to analyse engineering components as well as welded joints. Some success was also claimed for the determination of the stress intensity factors from the SPATE scan of a cracked specimen. The development of the SPATE SPECTRA (a version of SPATE which can handle random wave-form loading excitation) was also described.

(2) "Application of thermoelastic stress measurement to both modal analysis and the dynamic behaviour of electrical power plant structures" by R.G. Bream, B C. Gasper, S.W.J. Page and B.E. Lloyd of Central Electricity Generating Board, U.K. which was presented by Dr. Lionel Baker of Sira Ltd. It showed that SPATE can successfully be used to analyse the vibrational modes of a component under dynamic loads. It was pointed out that since SPATE's primary sensitivity is to stress rather than displacement as in many other optical techniques such as moire or holographic interferometry, the determination of stresses at nodal positions using SPATE data can be more accurate.

(3) "Application of thermoelastic stress techniques to fiber composites" by R.T. Potter and L.J. Greaves. This talk was presented by Mr. Potter of RAE, and discussed the difficulties in using SPATE on composites. Several parameters were considered which include loading frequency, surface resin thickness, and temperature dependent terms. To maintain adiabatic conditions, it was suggested that the testing frequency be at least 8 Hz. However, the accumulation of heat due to the energy dissipation of the matrix material at high frequency and high load amplitudes can be a potential problem. The surface resin thickness was found to have a substantial effect on the SPATE output. The reason for this was not understood. The study of the effect of the temperature dependent terms was initiated by the ARL's earlier work on the mean stress dependence of the thermoelastic parameter. In fact, the theoretical treatment followed the same approach as that of ARL's work. This led to the prediction that significant errors may arise if these terms were neglected. Experimental validation of this aspect has yet to be achieved.

(4) "Recent work on the stress dependence of the thermoelastic parameter" by A.K. Wong, J.G. Sparrow and S.A. Dunn. This was presented by the author, and covered a brief history of how ARL discovered the dependence of the SPATE output on the mean stress applied, and how the thermoelastic theory was re-derived to account for this apparent anomaly. The presentation mainly concentrated on a series of experiments designed to further validate the revised thermoelastic theory and how this may be exploited for the measurement of residual stresses. A copy of this paper is shown in Appendix I.

The author's presentation was well received and attracted much interest and useful comments. The following points were noted from the discussions:

- A large task group of experienced SPATE users has already been set up in the U.K. to look into ARL's findings.

- Efforts made in RAE and NEL have so far failed to yield any quantitative results on the mean stress dependence of the thermoelastic parameter. It was suggested that their SPATE's may be "noisier" than ours.

- There is an active and extensive SPATE research program being run in the University of Wisconsin, Madison, U.S.A. Of the eight current post-graduate students in the Fatigue Program run by the Engineering Mechanics Department, five are involved in researches associated with SPATE. Professor B. Sandor, who directs this program, pointed out that they are also aware of ARL's work, and experiments done in his department have confirmed our findings.

4. CONCLUSION

The visit was well worthwhile, serving not only to secure recognition for ARL's pioneering effort in the discovery of the mean stress dependence of the thermoelastic effect and the possible exploitation of this aspect for residual stress measurements, but also allowed the author to obtain useful feedback and to gauge the amount of effort being devoted to this work. It is felt that with the task group set up in the U.K., and the extensive research program run by the University of Wisconsin in the U.S., our "head-start" in trying to develop a practical thermoelastic residual stress method will soon be outstripped by the efforts made overseas.

Recent work on the stress dependence of the thermoelastic parameter

A. K. Wong, J. G. Sparrow and S. A. Dunn

Structures Division, Aeronautical Research Laboratories,
P. O. Box 4331, Melbourne, 3001, Australia.

SPIE Vol.817 Optomechanical Systems Engineering(1987)

ABSTRACT

In an earlier paper, a revised theory of the thermoelastic effect was presented which offers an explanation of the mean stress dependence of the thermoelastic parameter. Further experimental results are presented here to validate this theory, and to demonstrate that the predicted higher harmonic thermal response of a body under a single frequency excitation may be observed and measured. The presence of this higher harmonic response is due to the weak quadratic nature of the stress-temperature relationship. It is suggested that the ability to accurately measure this component may be the key to making practical residual stress measurements using this theory.

1. INTRODUCTION

The use of the thermoelastic effect for measuring surface stresses of a dynamically loaded body is now well established, and the commercially available instrument which makes use of this principle, SPATE 8000, is widely recognised as a powerful tool for non-contact full-field stress measurements[1-4]. Whilst emergence of SPATE may be considered as a relatively new break-through in stress analysis, the theory which forms the basis of its working principle has been known for well over a century. The first theoretical treatment of the thermal-mechanical coupling between temperature changes and stress changes dates back to 1855[5]. The resulting relationship, known as *Kelvin's Law*, states that under adiabatic conditions, the change in temperature δT is linearly related to the change in the sum of principal stresses δs, viz.

$$\frac{\delta T}{T_o} = -K\delta s, \tag{1}$$

in which T_o is the absolute temperature of the element under consideration, and K is known as the thermoelastic parameter (or more commonly, thermoelastic constant).

Since the SPATE response is linearly related to the amplitude of cyclic temperature change, the direct application of *Kelvin's Law* means that the SPATE response should be directly related to the amplitude of the cyclic principle stress sum. Further, the above equation infers that this response should be independent of the presence of any mean or steady state stress. However, recent work carried out in the Aeronautical Research Laboratories has revealed that the SPATE output is dependent not only on the amplitude of the cyclic stress, but also on the mean stress state. In a series of experiments whereby an applied mean load was varied whilst maintaining a constant load amplitude, Machin *et al*[6] showed that the thermoelastic parameter for the titanium and aluminium alloys tested were significantly dependent on the mean load. This apparent stress dependence of K had previously been observed by Belgen[7], where he found that the measured thermoelastic parameters for four metals tested were dependent on the size of the load excursions imposed on the specimens. Belgen conjectured that this behaviour could be due to the stress dependence of the "specific heat and/or Poisson's ratio". However, the extent of stress dependence of these properties must be substantial in order to explain the findings in Ref. 6, and reports of such dependence were not found in the literature. A theoretical study was subsequently undertaken by Wong *et al*[8] to re-examine the thermoelastic relationship, and to search for a more likely explanation for this interesting phenomenon. By a more generalised approach, it was shown in Ref. 8 that the stress dependence of the thermoelastic parameter may be fully accounted for by the temperature dependence of the elastic moduli of the material.

The purpose of this paper is to present a summary of the theoretical presentation, and to lend further experimental support to the theory derived in Ref. 8, as well as to highlight the potential of applying this theory as a means of measuring surface residual stresses.

2. THEORY

It was shown[8] that the revised form of the thermoelastic equation relating the rate of temperature change and the rate of change in stress state in a homogeneous Hookean material under adiabatic conditions can be written as

$$\begin{aligned}\rho_o C_\epsilon \frac{\dot{T}}{T} = &-\left[\alpha + \left(\frac{\nu}{E^2}\frac{\partial E}{\partial T} - \frac{1}{E}\frac{\partial \nu}{\partial T}\right)s\right]\dot{s} \\ &+ \left(\frac{(1+\nu)}{E^2}\frac{\partial E}{\partial T} - \frac{1}{E}\frac{\partial \nu}{\partial T}\right)\sum_{i=1}^{3}\sigma_{ii}\dot{\sigma}_{ii}\end{aligned} \tag{2}$$

in which

T is the thermodynamic temperature (K),
σ_{ii} are the principal stress components (N/m^2),
s is the sum of the principal stresses (N/m^2),
ρ_o is the density (kg/m^3),
C_ϵ is the specific heat under constant strain ($Nm/^\circ C$),
α is the coefficient of linear thermal expansion ($^\circ C^{-1}$),
E is the Young's modulus (N/m^2), and
ν is the Poisson's ratio.

Equation (2) differs from the classical thermoelastic equation in that the elastic moduli are not assumed to be constants, but are taken to be general functions of temperature. It may be seen that the temperature response is now dependent on both the stress rate as well as the stress state itself. Taking the uniaxial case as an illustrative example, in which

$$\sigma_1 = s, \qquad \sigma_2 = \sigma_3 = 0,$$
and
$$\dot{\sigma}_1 = \dot{s}, \qquad \dot{\sigma}_2 = \dot{\sigma}_3 = 0. \tag{3}$$

Equation (2) becomes

$$\rho_o C_\epsilon \frac{\dot{T}}{T} = -\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s\right)\dot{s}. \tag{4}$$

It was shown[8] that under an applied stress of the form

$$s = s_m + \Delta s \sin\omega t, \tag{5}$$

where s_m and Δs are the mean and amplitude of the applied stress respectively, and ω is the loading frequency, eqn (4) may be integrated to give

$$\rho_o C_\epsilon \frac{\delta T}{T_o} = -\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)\Delta s \sin\omega t + \frac{1}{4E^2}\frac{\partial E}{\partial T}(\Delta s)^2(1-\cos 2\omega t). \tag{6}$$

However, it was overlooked in Ref. 8 that any steady state component of δT cannot be sustained due to energy transfers to the surroundings. In other words, a valid adiabatic solution of δT which satisfies eqns (4) and (5) is given by

$$\rho_o C_\epsilon \frac{\delta T}{T_o} = -\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)\Delta s \sin\omega t - \frac{1}{4E^2}\frac{\partial E}{\partial T}(\Delta s)^2\cos 2\omega t. \tag{7}$$

Equation (7) shows that under a single frequency excitation, the temperature response contains two frequency components. However, because the correlator of SPATE has the effect of filtering out all harmonic components other than that of the loading frequency, SPATE records only the fundamental component. The effective thermoelastic parameter K as seen by SPATE is therefore given by

$$K = \left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)(\rho_o C_\epsilon)^{-1}. \tag{8}$$

Equation (8) shows the thermoelastic parameter to be a linear function of the mean stress s_m, and a normalised measure of its mean stress dependence is therefore

$$\frac{1}{K_o}\frac{\partial K}{\partial s_m} = -\frac{1}{\alpha E^2}\frac{\partial E}{\partial T}, \tag{9}$$

where $K_o = \alpha/(\rho_o C_\epsilon)$ is the usually adopted thermoelastic constant.

Since the right hand side of eqn (9) consists only of material parameters which are obtainable from the literature, this provides a convenient means for validating the revised thermoelastic relationship. Although $\partial E/\partial T$ data are usually much less common as compared to other material properties, such data are available for the titanium alloy Ti-6Al-4V[9] and the aluminium alloy Al-2024[10], both of which were considered in the experiments in Machin *et al*[6]. It was shown in Ref. 8 that good agreement between theory and the experiments was achieved (see Table 1).

In the following, this theory is further validated by an examination of the infrared detector signal prior to being processed by the SPATE correlator, and it will be shown that this raw signal obeys the response law as described by eqn (7), and more generally, eqn (4).

3. EXPERIMENTS

The experiments were carried out on a ±50 kN MTS servo-hydraulic fatigue testing machine, coupled with a Solartron 1250 transfer function analyser which acted as a function generator. This system was able to provide a near pure sinusoidal loading cycle over the frequency and load range considered.

After a series of preliminary trials, it was found that the titanium alloy Ti-6Al-4V was most suitable due to its relatively high $\partial E/\partial T$ value as well as possessing a high yield strength. Consequently, a cylindrical Ti-6Al-4V specimen was used throughout the tests. The specimen has a working section of 60 mm in length and a uniform cross-sectional diameter of 11.35 mm. Extreme care was taken in its alignment in the testing machine to achieve, essentially, a one-dimensional stress field near the mid-section of the specimen. To improve the emissivity of the specimen, the surface to be analysed was cleaned with acetone, and a thin coat of matt-black paint applied by means of an aerosol spray. SPATE was then focused on a fixed point in this region from a stand-off distance of approximately 50 cm.

3.1 Measurement of the second harmonic component

The first phase of the experiment was to demonstrate that under a pure sinusoidal loading cycle of frequency ω, the detector response contains two frequency components (ω and 2ω) in accordance with eqn (7). To achieve this, measurements of both the fundamental and second harmonic components of the raw SPATE detector signal were recorded over loads of different cyclic amplitudes ranging from ±10 kN (±98.8 MPa) to ±40 kN (±395.2 MPa). A zero mean load was maintained to maximise the cyclic range. The tests were repeated for several frequencies ranging from 5 to 20 Hz, and no apparent frequency dependence was found. A Wavetek 704A 4-channel FFT spectrum analyser was used to monitor both the purity of the loading cycle as well as to analyse the raw signal of the SPATE detector output. Analyser integration times of 10 and 30 seconds were found to be sufficient to give stable readings for the first and second harmonic components respectively.

Figure 1 shows a typical plot of the spectral content of the load cell output, where the lower frame is on an enlarged vertical scale. It may be seen that the loading cycle was nearly sinusoidal with very little contributions at other harmonics. Most importantly, the second harmonic component was extremely small and amounts to less than 0.1% of the fundamental signal. On the other hand, the spectral content of the detector signal, as shown in figure 2, reveals a significant contribution (amplitude of approximately 4% of the fundamental) at a frequency of 2ω.

One unexpected feature of the detector signal spectrum was the small spike at 16.7 Hz. This was found to be an artifact inherent to the SPATE system, as it was present even when the scanning unit door was shut and the MTS testing machine was turned off.

The test results are summarised in figures 3 to 5. It may

Material	α ($°C^{-1}$)	E (MPa)	$\partial E/\partial T$ (MPa/°C)	$(\partial K/\partial s_m)K_o^{-1}$ Theory (Eqn 9)	(MPa^{-1}) Experiments[6]
Ti-6Al-4V	9.0×10^{-6}	1.11×10^5	−48.0	4.33×10^{-4}	4.29×10^{-4}
Al-2024	2.3×10^{-5}	7.2×10^4	−36.0	3.02×10^{-4}	3.19×10^{-4}

Table 1. Comparison of theoretical and measured mean stress dependence of K (from Ref. 8).

be seen from figure 3 that the first harmonic response is linearly related to the cyclic stress amplitude, and a best fit of the form $S_\omega = a\Delta s$ yields $a = 8.63 \times 10^{-3}$ mV/MPa, and a correlation coefficient of $r = 0.992$. This linear relationship is in agreement with theory where the slope a is directly related to the thermoelastic parameter K. If the mean stress were to deviate from zero, then the slope of this line would be changed according to eqn (9). The mean stress dependence of the thermoelastic parameter is not shown here as this has previously been demonstrated[6].

The second harmonic response is shown in figure 4. According to the revised theory, the 2ω component should be linearly proportional to the square of the cyclic stress amplitude as shown in eqn (7). Although the scatter is much larger than that for the fundamental response, as the signal to noise ratio was much lower, a line of best fit of the form $S_{2\omega} = b\Delta s^2$ shows good correlation ($r = 0.967$) and gives $b = 9.74 \times 10^{-6}$ mV/MPa^2. The ratios of these two slopes (b/a) is therefore 1.13×10^{-4} MPa^{-1}. On the other hand, a theoretical prediction may be obtained from eqn (7), where it

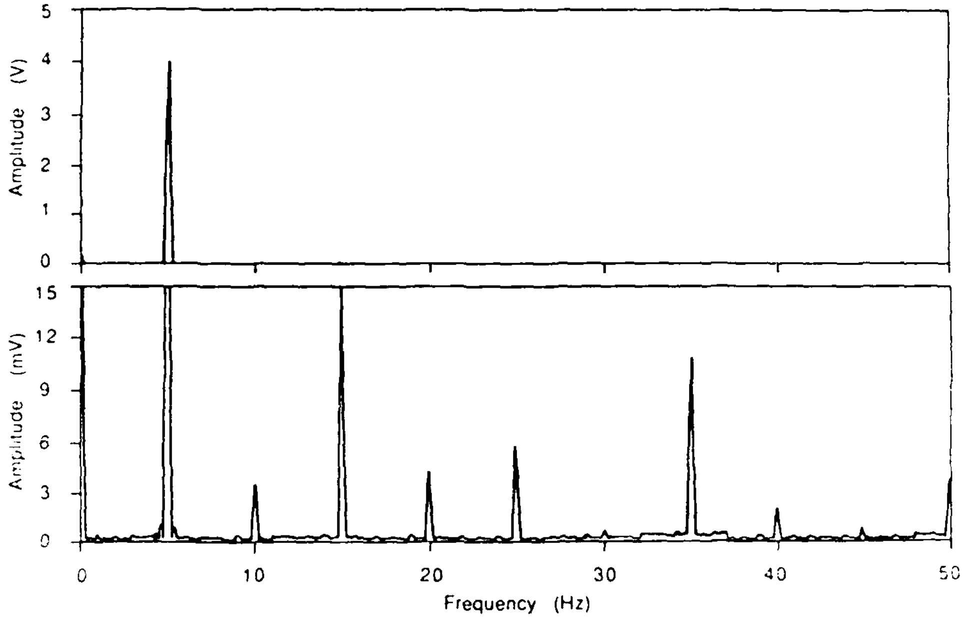


Fig. 1. A typical load spectrum for a 5 Hz load.

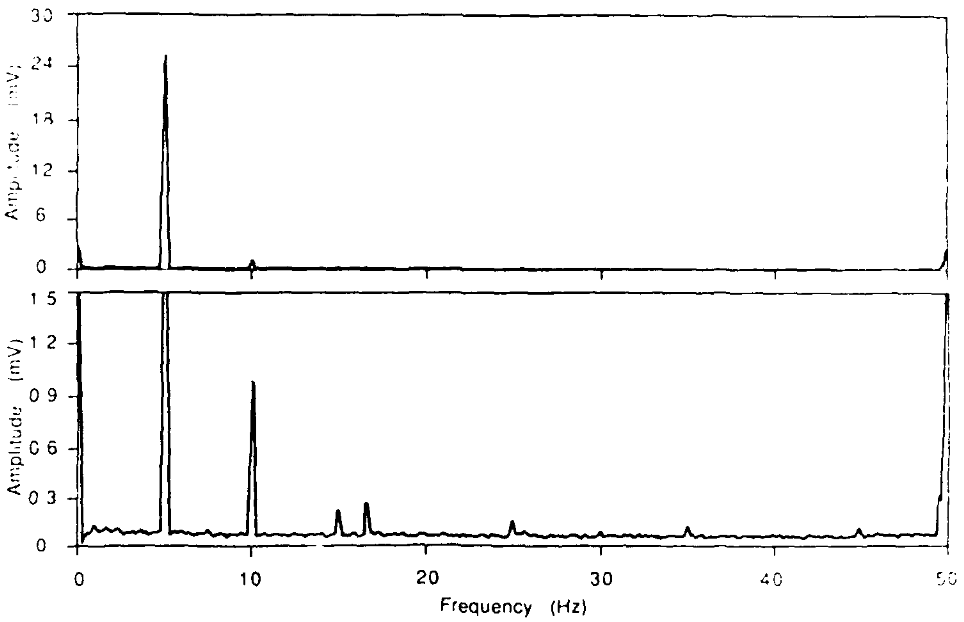


Fig. 2. A typical SPATE spectrum for a 5 Hz load.

may be seen that under zero mean stress, and noting that the recorded detector voltages were r.m.s. measurements, the ratio of the slopes may be given by

$$\frac{b}{a} = \left| \frac{1}{4\alpha E^2} \frac{\partial E}{\partial T} \right| . \qquad (10)$$

Since $-(\alpha E^2)^{-1} \partial E / \partial T = 4.33 \times 10^{-4} \mathrm{MPa}^{-1}$, eqn (10) gives a predicted b/a ratio of $1.08 \times 10^{-4} \mathrm{MPa}^{-1}$ which is in good agreement with the experimental result.

Phase measurements for the second harmonic response were also taken, and are presented in figure 5. Because it is difficult to compare phases between two wave forms of different frequencies, and since the system lag was found to be a constant time lag which was relatively insensitive to the amplitude, phase lags of the second harmonic component were assumed to be the difference between the second harmonic phase readings and the phase readings of the first harmonic at twice the frequency. The results strongly support a cosine form for the second harmonic response as suggested in eqn (7).

Although the second order component of the thermal response is extremely small compared to the primary signal, the fact that it can be successfully measured strengthens the possibility of applying this theory for measuring residual stresses. In the above example for instance, assuming that all material properties may be obtained accurately, it may be seen from eqn (7) that the ability to simultaneously measure and record the fundamental and the second harmonic components of the temperature response will be sufficient to enable both the cyclic and the mean (or initial) components of stress to be calculated. This has the important implication that surface residual stresses may be evaluated with this method. Of course, this problem becomes much more difficult for the multiaxial case. Besides the increased mathematical complexity for such cases, the locations of high residual stresses may not coincide with high applied cyclic stresses so that measurement of the second order term may be impractical. However, with a better noise suppression algorithm, and perhaps a more sensitive detector, there is immense potential for turning SPATE into a residual stress measuring device. Preliminary tests on specimens which contain residual stresses induced by four-point bending have proved to be promising, and the final results will be presented elsewhere.

3.2 The general response law

In the previous section, it was shown that when a body is loaded at a single frequency ω, the temperature (and thus the detector signal) response contains two frequencies ω and 2ω. This is due to a non-linearity in the response law as described by eqn (2). Consider the one-dimensional case as an example, a simple manipulation of eqn (4) gives

$$\rho_0 C_\epsilon \frac{\dot{T}}{T} = -\frac{\partial}{\partial t} \left(\alpha s - \frac{1}{2E^2} \frac{\partial E}{\partial T} s^2 \right) . \qquad (11)$$

For $\delta T = T - T_0 \ll T_0$, the integration of both sides of eqn (11) yields

$$\rho_0 C_\epsilon \frac{\delta T}{T_0} = -\alpha s + \frac{1}{2E^2} \frac{\partial E}{\partial T} s^2 + k, \qquad (12)$$

where k is an integration constant. For a valid adiabatic solution of δT under a periodic stress waveform, k is given by

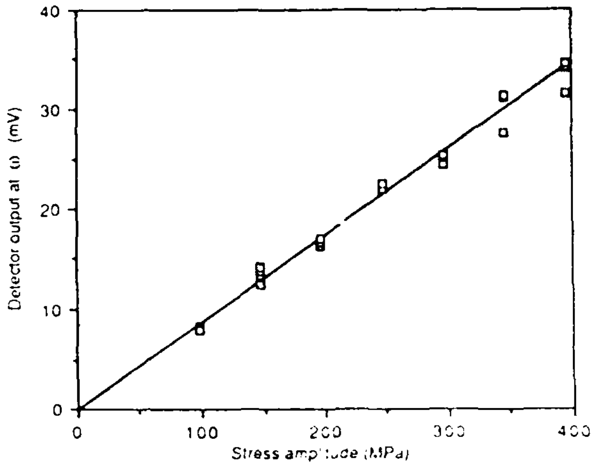


Fig. 3. First harmonic detector output.

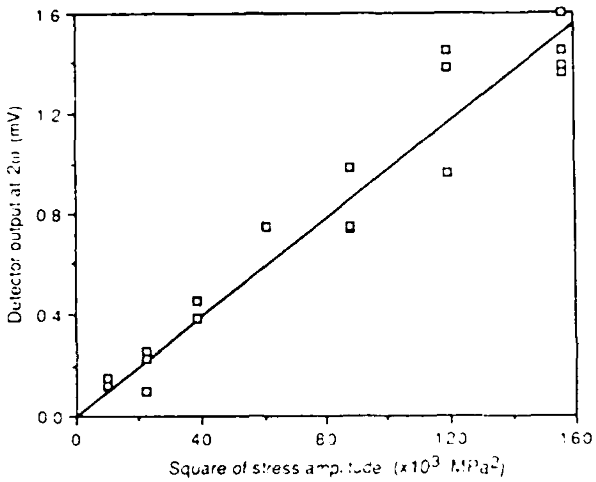


Fig. 4. Second harmonic detector output.

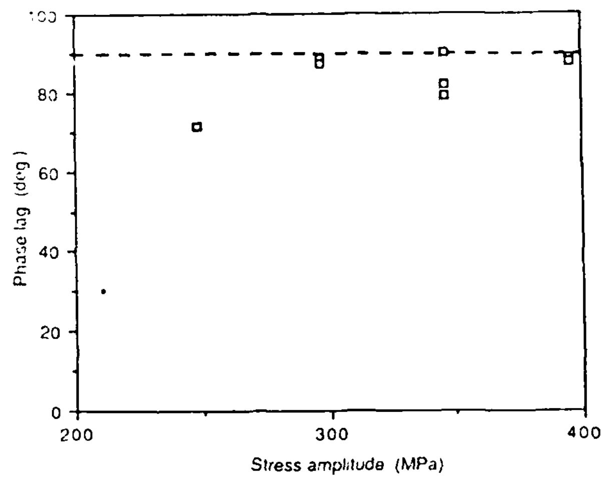


Fig. 5. Second harmonic phase lag of detector output.

$$k = \lim_{\tau} \frac{\alpha \int_0^{\tau} s\,dt - \frac{1}{2E^2} \int_0^{\tau} s^2\,dt}{\tau}. \tag{13}$$

Equation (12) shows that the relationship between the detector signal and the applied stress should be quadratic in form, viz.

$$S = a_o + a_1 s + a_2 s^2, \tag{14}$$

in which a_1 and a_2 are material constants, and their ratio is given by

$$\frac{a_2}{a_1} = -\frac{1}{2\alpha E^2}\frac{\partial E}{\partial T}. \tag{15}$$

To show the validity of this response law, the same specimen was stressed under a series of 5 Hz loads of various amplitudes, with both the load cell and raw detector signal collected simultaneously by a Hewlett Packard 7090A Measurement Plotting System. For each run, the analogue signals were suitably amplified to minimise quantisation errors and were sampled at 500 Hz over a 2 second interval. Because the raw detector signal was observed to possess a relatively high white noise content, a 30 Hz low-pass filter was used to remove much of the high frequency noise. A similar filter was also used on the load cell signal to remove the 50 Hz mains pick-up as well as to match the phase shift of the signals induced by such filters.

The resultant 1000 data pairs were subsequently transferred to a computer for processing. Due to the difference in the load cell and detector response characteristics, a small phase difference was apparent in the data sets. A computer program was developed to adjust for this phase difference by realigning the data sets, and to perform a least squares fit of the form of eqn (14). The result of this analysis is summarised in Table 2, where it can be seen that the measured coefficients a_1 and a_2 were found to be practically constant, and their ratio in close agreement with the present theory.

Load Amplitude (kN)	a_1 (mV/MPa) $\times 10^{-2}$	a_2 (mV/MPa^2) $\times 10^{-6}$	a_2/a_1 (MPa^{-1}) $\times 10^{-4}$
25.0	2.913	6.323	2.171
25.0	2.800	6.593	2.355
30.0	2.897	6.143	2.120
30.0	2.844	6.155	2.164
32.5	2.864	6.192	2.162
35.0	2.907	5.413	1.862
Mean	2.87	6.14	2.14†
Standard Error	0.02	0.16	0.06

† cf theoretically predicted value of $a_2/a_1 = 2.16 \times 10^{-4}$ MPa^{-1} (see eqn (15)).

Table 2. Coefficients of the general response law relating stress and the detector signal.

In the above tests, because no prior assumption of wave form was made, there was no requirement for a single-frequency loading cycle. Hence, whilst a series of nominally sinusoidal loads were used for convenience, there was no real concern for maintaining a strictly pure sinusoidal wave form as was required in the previous section. Further, because of the quadratic nature of the response law, it may be easily shown that the presence of any two components in the loading wave form at frequencies $n\omega$ and $(n+2)\omega$ will contribute to the thermal output at the second harmonic frequency. In particular, because the fundamental component is expected to be large, the presence of any sizeable third harmonic load can therefore contribute significantly to the second harmonic thermal response. This could perhaps explain the relatively large scatter in the measurements presented in figure 4, and also highlights the need to ensure a pure sinusoidal loading wave form if the technique of the previous section were to be developed for predicting residual stresses.

4. CONCLUSION

The revised theory of the thermoelastic effect derived in Wong *et al*[8] showed that the recorded SPATE signal is dependent on the mean stress, and thereby explains the earlier experimental findings[6]. From the new theory, it was postulated in Ref. 8 that when a body is subjected to a cyclic load of frequency ω, the corresponding thermal signal should contain components at frequencies ω and 2ω. This phenomenon was demonstrated in the present paper by analysing the raw detector signal of SPATE. It was also shown that the higher harmonic component arises due to the quadratic nature of the response law.

It has been concluded that the ability to accurately measure the higher order term of the thermal response strengthens the possibility of applying the present theory for the measurement of surface residual stresses of a material. The development of a better noise suppression algorithm and/or a more sensitive detector would undoubtedly expedite the realisation of this most important goal.

5. ACKNOWLEDEMENTS

The authors wish to acknowledge the most invaluable assistance, advice and encouragements from Messrs P. Farrell, M. Stimson and Drs R. Jones and T. Ryall.

6. REFERENCES

1. Harwood N., "Relative assessment of full field experimental stress analysis techniques", *Strain* **20**, 119 (1984).
2. Harwood N. and Cummings W.M., "Application of thermoelastic stress analysis", *Strain* **22**, 7 (1986).
3. Stanley P. and Chan W.K., "Quantitative stress analysis by means of the thermoelastic effect", *J. Strain Analysis* **20**, 129 (1985).
4. Machin A.S. and Sparrow J.G., "The SPATE 8000 thermoelastic stress analyser", *Non-destructive Testing Australia*, **23**, 96 (1986).
5. Thomson W. (Lord Kelvin), "On the thermo-elastic and thermo-magnetic properties of matter", *Q. J. Maths.* **1**, 55 (1855), reprinted in *Phil. Mag.*, **5**, 4 (1878).
6. Machin A.S., Sparrow J.G. and Stimson M-G., "Mean stress dependence of the thermoelastic constant", *Strain* **23**, 27 (1987).
7. Belgen M.H., "Infrared radiometric stress instrumentation application range study", *NASA Contr. Rept. CR-1067*, May (1968).
8. Wong A.K., Jones R. and Sparrow J.G., "Thermoelastic constant or thermoelastic parameter ?", *J. Phys. Chem. Solids -in press.*
9. Metals Handbook, *9th Edition*, **3**, (1980).
10. Brammer J.A. and Percival C.M., "Elevated-temperature elastic moduli of 2024 aluminum obtained by a laser-pulse technique", *Experimental Mechanics*, **10**, 245 (1970).

DISTRIBUTION

AUSTRALIA

Department of Defence

Defence Central
Chief Defence Scientist
Assist Chief Defence Scientist, Operations (shared copy)
Assist Chief Defence Scientist, Policy (shared copy)
Director, Departmental Publications
Counsellor, Defence Science (London) (Doc Data sheet only)
Counsellor, Defence Science (Washington) (Doc Data sheet only)
S.A. to Thailand Military R and D (Doc Data sheet only)
S.A. to the DRC (Kuala Lumpur) (Doc Data sheet only)
OIC TRS, Defence Central Library
Document Exchange Centre, DISB (18 copies)
Joint Intelligence Organisation
Librarian H Block, Victoria Barracks, Melbourne
Director General - Army Development (NSO) (4 copies)

Aeronautical Research Laboratory
Director
Library
Divisional File - Aircraft Structures
Author: A.K. Wong
S.A. Dunn
R. Jones
J.G. Sparrow

Materials Research Laboratory
Director/Library

Defence Science & Technology Organisation - Salisbury
Library

Navy Office
Navy Scientific Adviser

Army Office
Scientific Adviser - Army
Engineering Development Establishment, Library
Royal Military College Library

Air Force Office
Air Force Scientific Adviser
Technical Division Library
Director General Aircraft Engineering - Air Force

Universities and Colleges

NSW

Library, Australian Defence Force Academy

SPARES (10 copies)

TOTAL (55 copies)

AL 149
REVISED DECEMBER 87

DEPARTMENT OF DEFENCE

DOCUMENT CONTROL DATA

PAGE CLASSIFICATION
UNCLASSIFIED

PRIVACY MARKING

1a. AR NUMBER	1b. ESTABLISHMENT NUMBER	2. DOCUMENT DATE	3. TASK NUMBER
AR-004-590	ARL/STRUC-TM-481	FEBRUARY 1988	DST 87/038

4. TITLE	5. SECURITY CLASSIFICATION	6. No. PAGES / 7. No. REFS.
REPORT ON AN OVERSEAS VISIT TO USA RELATING TO THE THERMO-ELASTIC MEASUREMENT OF STRESSES, 16-21 AUGUST 1987	(PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONFIDENTIAL (C), RESTRICTED (R), UNCLASSIFIED (U).) U DOCUMENT, U TITLE, U ABSTRACT	6. No. PAGES: 9; 7. No. REFS.: 10

8. AUTHOR(S)	9. DOWNGRADING/DELIMITING INSTRUCTIONS
A.K. WONG	

10. CORPORATE AUTHOR AND ADDRESS	11. OFFICE/POSITION RESPONSIBLE FOR
AERONAUTICAL RESEARCH LABORATORY P.O. BOX 4331, MELBOURNE VIC. 3001	SPONSOR ______ SECURITY ______ DOWNGRADING ______ APPROVAL ______

12. SECONDARY DISTRIBUTION (OF THIS DOCUMENT) Approved for public release.

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH ASDIS, DEFENCE INFORMATION SERVICES BRANCH, DEPARTMENT OF DEFENCE, CAMPBELL PARK, CANBERRA, ACT 2601

13a. THIS DOCUMENT MAY BE ANNOUNCED IN CATALOGUES AND AWARENESS SERVICES AVAILABLE TO.....
No limitations

13b. CITATION FOR OTHER PURPOSES (IE. CASUAL ANNOUNCEMENT) MAY BE [X] UNRESTRICTED OR [ ] AS FOR 13a.

14. DESCRIPTORS	15. DRDA SUBJECT CATEGORIES
Thermoelasticity Stress analysis Nondestructive tests Spate Strain measurement	0094J 0046E

16. ABSTRACT

This report describes a short overseas visit made by the author to the United States in 1987. The purpose of the visit was to attend the 31st Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, and to present an invited paper.

LMED

8